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OBSERVATIONAL EVIDENCE FOR AN AGE DEPENDENCE OF HALO BIAS

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ABSTRACT

We study the dependence of the cross-correlation between galaxies and galaxy groups on group properties. Confirming previous results, we find that the correlation strength is stronger for more massive groups, in good agreement with the expected mass dependence of halo bias. We also find, however, that for groups of the same mass, the correlation strength depends on the star formation rate (SFR) of the central galaxy: at fixed mass, the bias of galaxy groups decreases as the SFR of the central galaxy increases. We discuss these findings in light of the recent findings by Gao et al. (2005) that halo bias depends on halo formation time, in that halos that assemble earlier are more strongly biased. We also discuss the implication for galaxy formation, and address a possible link to galaxy conformity, the observed correlation between the properties of satellite galaxies and those of their central galaxy.

Subject headings: dark matter - large-scale structure of the universe - galaxies: halos

1. INTRODUCTION

In the standard cold dark matter (CDM) paradigm of structure formation, virialized CDM halos are considered to be the building blocks of the mass distribution in the Universe. The properties of dark matter halos, as well as their formation histories and clustering properties, have been studied in great detail using both numerical simulations as well as analytical approaches such as the (extended) Press Schechter formalism. These studies have shown that halo bias is mass dependent, in that more massive halos are more strongly clustered (e.g., Mo & White 1996; Seljak & Warren 2004). This mass dependence of the halo bias has played a crucial role in understanding the correlation function of both dark matter and galaxies, via the so-called halo model (e.g., Cooray & Sheth 2002), the halo occupation models (e.g., Berlind & Weinberg 2002), and the conditional luminosity function (e.g., Yang, Mo & van den Bosch 2003).

Recently, Gao et al. (2005) used a very large, high resolution numerical simulation of structure formation in a ΛCDM cosmology to reexamine halo bias. They found that for halos at redshift $z = 0$ with $M \lesssim 10^{13} h^{-1}\,\mathrm{M}_\odot$ the bias depends not only on mass but also on the halo assembly time. If the properties of galaxies depend on the assembly time of their parent halo, this may have an important impact on the accuracy of halo occupation models and the conditional luminosity function, both of which implicitly assume that halo bias only depends on halo mass.

Since dark matter halos are thought to mark the locations where galaxies form and reside, a promising way to study halo bias observationally is via the clustering properties of galaxy groups. In what follows we use a very liberal definition of a galaxy group, including any system of galaxies that belongs to the same dark matter halo. This includes galaxy clusters as well as halos that host only a single galaxy (i.e., single member galaxy 'groups'). With the advent of large galaxy redshift surveys, it is now possible to construct very large group catalogues, which allow an accurate, statistical study of their clustering properties (e.g., Merchan & Zandivarez 2002; Zandivarez et al. 2003; Yang et al. 2005b,d; Coil et al. 2005). In addition, these catalogues allow for a detailed study of how the properties of the galaxy population depend on the properties of the halo in which they reside (Eke et al. 2004; Yang et al. 2005c; Weinmann et al. 2005).

In this Letter we use the galaxy-group cross-correlation function (hereafter GGCCF) to study its dependence on the properties of the central galaxies of the groups. In Section 2 we describe the data and the method used for our analysis, the results of which are presented in Section 3. A discussion of the implications of our results for the age dependence of halo bias and for galaxy conformity are discussed in Section 4.

2. DATA AND ANALYSIS

Our analysis is based on the group catalogue of Yang et al. (2005a; hereafter YMBJ), constructed from the 2-degree Field Galaxy Redshift Survey (hereafter 2dFGRS; Colless et al. 2001). This catalogue is constructed with a new, halo-based group finder which has been optimized to assign galaxies into groups according to their common dark matter halos. Group masses are estimated from the ranking of group luminosity, as described in detail in Yang et al. (2005c). As shown in Weinmann et al. (2005), this method yields masses that are more accurate than those based on the more traditional velocity dispersion of the group members. However, it requires knowledge of the halo mass function, and is therefore cosmology dependent. Throughout we adopt a ΛCDM 'concordance' cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$ and $\sigma_8 = 0.9$. We use the form given in Sheth, Mo & Tormen (2001) for the halo mass function.

In Yang et al. (2005d) we used this group catalogue to study the GGCCF to quantify the spatial distribu-

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TABLE 1
GALAXY AND GROUP SAMPLES.

Mass bin	z	$N_{\rm group}$	$N_{\rm galaxy}$	Mean η_c	b_{rel}
$12.0 \le \log(M_{\rm h}/h^{-1}\,{\rm M}_{\odot}) \le 12.5$	[0.03 0.11]	7789	14993	2.73/-0.28/-1.78/-2.85	0.76/0.93/0.95/1.18
$12.5 \le \log(M_{\rm h}/h^{-1}\,{\rm M}_{\odot}) \le 13.0$	[0.03 0.16]	10984	45139	2.06/-0.92/-2.19/-3.05	1.11/1.16/1.31/1.47
$13.0 \le \log(M_{\rm h}/h^{-1}\,{\rm M}_{\odot}) \le 13.5$	[0.03 0.16]	3829	45139	0.89/-1.70/-2.49/-3.16	1.30/1.36/1.50/1.82
$13.5 \le \log(M_{\rm h}/h^{-1}\,{\rm M}_{\odot}) \le 14.0$	[0.03 0.16]	1117	45139	0.07/-2.10/-2.68/-3.32	2.00/2.06/2.56/2.77

NOTE. — Columns 1 and 2 list the mass range and redshift limit of each group sample. The numbers of groups and galaxies (with $-21.5 \le M_{b_J} - 5\log h \le -19.5$) in each of these samples are listed in columns 3 and 4. Groups in each sample are subdivided into four subsamples, each containing one quarter of the total sample, according to the value of the spectral index, η_c, of the central galaxy. The mean values of η_c and relative bias b_{rel} for each of these subsamples are indicated in columns 5 and 6.

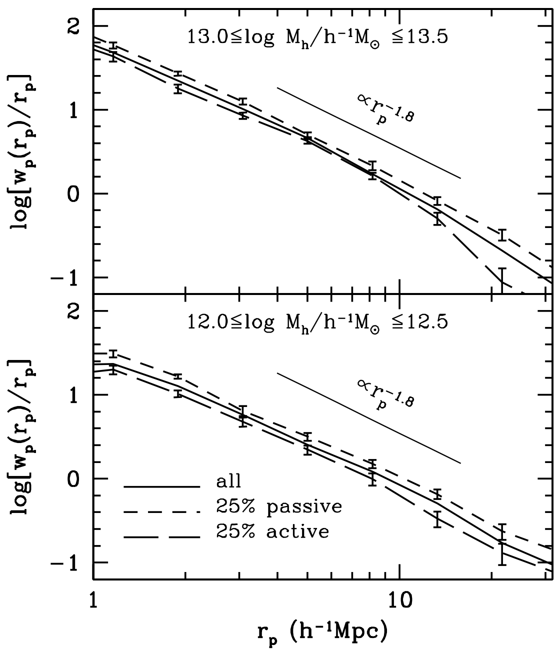

FIG. 1.— Solid lines show the projected galaxy-group cross correlation function (GGCCF). The upper and lower panels correspond to different group mass bins, as indicated. For each mass bin, the short-dashed curves indicate the GGCCF for the subsample with the In this Letter we use the galaxy-group cross-correlation function (hereafter GGCCF) to study its dependence on the properties of the central galaxies of the groups. In Section 2 we describe the data and the method used for our analysis, the results of which are presented in Section 3. A discussion of the implications of our results for the age dependence of halo bias and for galaxy conformity are discussed in Section 4. 25% lowest values of η_c (i.e., the central galaxies with the most passive star formation), while the long-dashed curves correspond to the subsample with the 25% highest values of η_c (the most actively star forming central galaxies). Errorbars indicate the 1-σ variance as obtained from 8 independent mocks.

tion of galaxies within CDM halos (see also Collister & Lahav 2005; Paz et al. 2005). In this Letter, we extend this analysis to study how the GGCCF depends on the properties of the central group galaxies. Motivated by the current paradigm of galaxy formation, we define the central galaxy as the brightest group member and we consider the location of the central galaxy to coincide with the centre of mass of the group. Note that we use the GGCCF instead of the auto-correlation of groups, because the much larger number of galaxies (compared to the number of groups) allows a much more accurate determination of the correlation power of the groups.

We split our group sample, at fixed group mass, according to the star formation rate (hereafter SFR) of the central galaxy. To this extent we use the parameter η, which is a linear combination of the two most significant principal components of the 2dFGRS galaxy spectra. As shown in Madgwick et al. (2002), η follows a bimodal distribution and is tightly correlated with the current SFR. Galaxies with $\eta \lesssim -1.4$ are mostly early-type galaxies with passive star formation, while those with $\eta \gtrsim -1.4$ are mainly actively star forming, late-type galaxies. We divide our group sample into four mass bins. Each of these is further subdivided into 4 equal-sized subsamples according to the value of η_c of the central galaxy (the subscript c refers to the central galaxy). Since for a given group mass the catalogue is only complete out to a certain redshift limit (see Yang et al. 2005d for details), we restrict the redshift range to $0.03 \le z \le 0.11$ for the lowest mass bin, and to $0.03 \le z \le 0.16$ for all other mass bins. For the galaxies, we use volume-limited samples with absolute magnitude $-21.5 \le M_{b_J} - 5\log h \le -19.5$. The various group and galaxy samples used are listed in Table 1.

In redshift space, the separation between a group center and a galaxy can be split in the components perpendicular, r_p, and parallel, π, to the line-of-sight. We compute the GGCCF, $\xi(r_p, \pi)$, using a symmetrized version of the Landy & Szalay (1993) estimator (see Coil et al. 2005). The random samples used for this estimator are generated taking all known observational selection effects into account (see Yang et al. 2005d). As a measure of the real space correlation function we use the projected GGCCF, defined as

$$w_p(r_p) = \int_{-\infty}^{\infty} \xi(r_p, \pi) {\rm d}\pi \,. \qquad (1)$$

In practice, we only integrate over the range $|\pi| \le 40\,h^{-1}$Mpc, which suffices to capture all relevant correlation power.

3. RESULTS

Fig. 1 shows the projected GGCCF for groups with masses $12.0 \le \log(M_{\rm h}/h^{-1}\,{\rm M}_{\odot}) \le 12.5$ (lower panel) and $13.0 \le \log(M_{\rm h}/h^{-1}{\rm M}_{\odot}) \le 13.5$ (upper panel). Solid lines indicate the results for *all* groups in the corresponding mass bin, while short-dashed and long-dashed lines correspond to the subsamples with the 25% lowest and highest values of η_c, respectively. Clearly, groups with a more passive central galaxy (i.e., a lower value of η_c) have a higher cross-correlation amplitude. Since the same galaxies are used in the estimation of these GGCCFs,

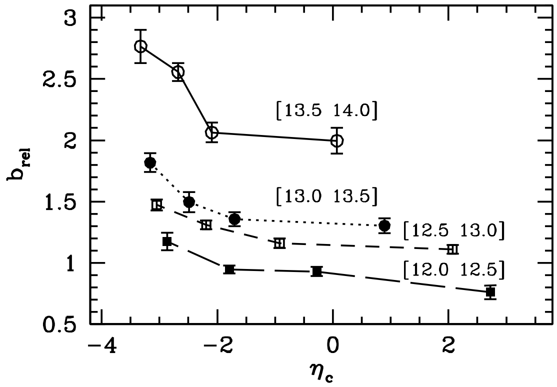

FIG. 2.— The relative bias, $b_{\rm rel}$, for groups in 4 mass bins as a function of η_c. Different symbols plus linestyles reflect different mass bins, with the values in square brackets indicating the range of $\log(M_h/h^{-1}\,{\rm M}_\odot)$. For each mass bin, the 4 subsamples all contain the same number of groups, and the value of η_c plotted is the average value for the corresponding subsample. The offset between the curves for the different mass bins reflects the mass dependence of the halo bias. For groups of the same mass, however, these is also a η_c-dependence: groups in which the central galaxy has a more passive star formation (i.e., a lower value of η_c) are more strongly clustered.

the relative amplitude between them is a measure of the relative clustering bias of the different groups.

For $r_p \gtrsim 3h^{-1}$Mpc, all the GGCCFs are well described by a power law, $w_p(r_p) \propto r_p^{-0.8}$. As discussed in Yang et al. (2005d), on these scales the GGCCF is dominated by the '2-halo' term, which is determined by the halo-halo correlation. In order to determine the relative bias of different groups, we fit all the projected GGCCFs in the range $3 \le r_p \le 30\,h^{-1}$Mpc with the power-law,

$$w_p(r_p) = A\, b_{\rm rel}\, r_p^{-0.8}\,, \tag{2}$$

where we set $A = 50$ so that $b_{\rm rel} \approx 1$ for the full sample of all groups with $12.0 \le \log(M_{\rm h}/h^{-1}\,{\rm M}_\odot) \le 12.5$. The values of $b_{\rm rel}$ thus obtained are shown in Fig 2 for groups with different values of η_c. The errorbars here are estimated from the 1-σ scatter among 8 mock samples (see YMBJ). As one can see, the relative bias increases strongly with group mass, as expected from the mass dependence of the halo bias (e.g., Mo & White 1996; Seljak & Warren 2004) and is consistent with earlier observational results (Padilla 2004; Yang et al. 2005b,d). For a given mass bin, there is a clear trend that groups with a smaller η_c (i.e., with a more passive central galaxy) have higher $b_{\rm rel}$. The ratio of $b_{\rm rel}$ between the quarters with the smallest and the highest values of η_c is about 1.4-1.6 for each of the four mass bins.

The group masses used above have been determined assuming a one-to-one relation between halo mass and the group luminosity in the b_J-band. One might argue that halo mass is more closely associated with the total *stellar* mass of the galaxies, rather than with the blue light. If this is indeed the case, our method of assigning halo masses may introduce an artificial η_c-dependence: a halo with a lot of recent star formation (i.e., with a high η_c value) will be overly luminous in the b_J-band, so that we will overestimate its mass. Since lower mass haloes are less strongly biased, this could in principle result in a false detection of η_c-dependence of halo bias. For relatively rich groups we can test this using the velocity dispersion of the member galaxies as a dynamical mass estimator. In Fig. 3 we show the relative bias as a function of η_c for groups with 4 member or more that have a velocity dispersion in the range of $250\,{\rm km\,s^{-1}}$ to $500\,{\rm km\,s^{-1}}$. Here again the relative bias increases as η_c decreases, suggesting that the η_c-dependence of $b_{\rm rel}$ is not simply due to systematic errors in our halo masses.

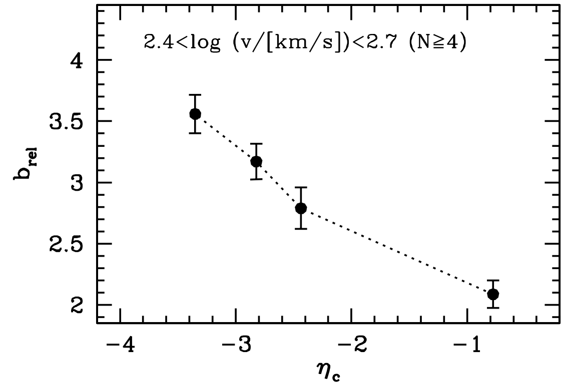

FIG. 3.— The same as Fig. 2, but here the mass of each group is estimated from the velocity dispersion of its member galaxies.

For poor groups where the velocity dispersion is not a reliable mass estimator, we test our results using the total *stellar* mass, instead of the total b_J-band luminosity, to determine group masses. Using the 9200 galaxies in the 2dFGRS that are also included in the Sloan Digital Sky Survey (SDSS; NYU-VAGC Blanton et al. 2005), we find a mean relation between the stellar mass-to-light ratio M_*/L_{b_J} and η given by

$$\log\,[M_*/L_{b_J}] = -0.088\eta + 0.587\,. \tag{3}$$

The stellar masses for these galaxies are obtained from the SDSS spectra as described in Kauffmann et al. (2003). Using eq.(3) we compute M_* for all galaxies in our 2dFGRS group catalogue, and estimate the halo masses using the total stellar mass of all group members. The resulting relations between $b_{\rm rel}$ and η_c are shown in Fig. 4. Note that there is still a significant η_c-dependence at fixed halo mass. Nevertheless, there are some differences with respect to the results shown in Fig. 2. In particular, for the bins with the highest η_c values, the relative bias has increased with respect to using the group luminosity to assign the halo masses. This owes to the effect discussed above, and is particularly pronounced for the mass bin $\log(M_h/h^{-1}\,{\rm M}_\odot) = [13.0 - 13.5]$. For less massive haloes the effect is weaker, simply because for haloes with $M \lesssim 10^{13}h^{-1}\,{\rm M}_\odot$ the halo bias only depends weakly on M, so that an error in halo mass has only a small effect. For the most massive haloes, the effect is also much weaker, basically because for these systems the luminosity of the central galaxy is only a small fraction of the total group luminosity. We wish to stress that since it is not *a priori* clear whether halo mass is more tightly correlated with stellar mass or with b_J-band luminosity, it is not clear which of the results (Fig. 2 or Fig. 4) are the more accurate. Overall, however, our results indicate a clear η_c dependence of halo bias. An accurate measurement of the absolute strength of this effect, however, requires a more robust determination of halo masses.

4. DISCUSSION

Galaxies are thought to form in CDM halos, and it is generally assumed that galaxy properties are only deter-

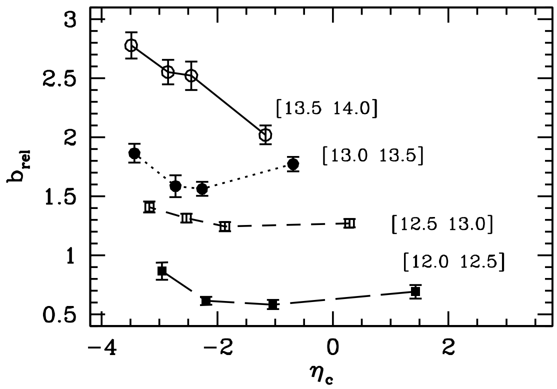

FIG. 4.— The same as Fig. 2, but here the mass of each group is based on the total stellar mass of its member galaxies.

mined by the properties of their host halo (e.g., mass, angular momentum, formation history, etc.). In particular, in the 'standard' picture, adopted in all semi-analytical models of galaxy formation, the morphology of a central galaxy is related to the epoch of the last major merger: halos that experienced their last major merger more recently (i.e., that assembled later) are more likely to host an early type (passive) central galaxy. Based on the results of Gao et al. (2005), one would expect halos with a passive central galaxy to be less strongly clustered than halos of the same mass, but with a late type (active) central galaxy, contrary to the results presented here. In order to explain the SFR dependence of the halo bias, one needs a mechanism that shuts off the star formation of the central galaxy earlier in a halo that assembles earlier. For example, if the time of the last major merger also signals the time at which star formation is terminated, a redder central galaxy may be produced by an earlier major merger. The age dependence of the halo bias would then be in qualitative agreement with the results presented here. Interestingly, a similar truncation of star formation seems also required in order to explain the bright end of the galaxy luminosity function, and may be related to AGN feedback (e.g., Benson et al. 2003; Granato et al. 2004; Nagashima et al. 2004; Croton et al. 2005). It remains to be seen whether semi-analytical models that take such feedback processes into account can indeed explain the clustering dependencies presented here.

It is also interesting to link the results presented here to galaxy conformity. As shown in Weinmann et al. (2005), halos with an early type central galaxy have a significantly larger fraction of early type satellites than a halo of the same mass, but with a late type central galaxy. The results presented here, therefore, suggest a bias that depends not only on the properties of the *central* galaxy, but also on those of the *entire* galaxy population of the group. A halo that assembled earlier will have typically accreted its satellite population earlier. It is generally assumed that once a galaxy becomes a satellite galaxy of a bigger system, its star formation is truncated, either because the galaxy loses its hot gas supply (Larson, Tinsley & Caldwell 1980), or because ram pressure stripping removes the cold gas supply. This would suggest that halos with a larger fraction of early type (passive) satellites assembled earlier. The age dependence of the halo bias then implies that these systems should be more strongly clustered, in qualitative agreement with the results presented here.

However, a number of open questions remain. First of all, Gao et al. (2005) only detected an age dependence of halo bias for halos with masses below the characteristic non-linear mass scale $M^* \simeq 10^{13}h^{-1}\,\mathrm{M}_\odot$, whereas we find that the more massive halos also reveal an η_c-dependence. Second, it is unclear how the halo formation time, defined in Gao et al. (2005) as the time when a halo assembles half of it mass, is related to the age of the galaxies that form in the halo. Numerical simulations and semi-analytical models are required to investigate these issues in detail.

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